Abstract

ABSTRACT

Purpose: There is a scarcity of information on the long term adaptations in lower limb biomechanics during game specific movements after an anterior cruciate ligament (ACL) reconstruction. Particularly, variables such as knee abduction moments and transverse plane knee motion have not been studied during a game specific landing and cutting task after ACL reconstruction. The purpose of this study was to compare the hip and knee mechanics between the ACL reconstructed (ACLr) group and a healthy control group.

Methods: 38 athletes (18 ACLr, 18 control) participated in the study. Three dimensional hip, knee and ankle angles were calculated during a maximal drop jump land from a 0.30 m box and unanticipated cutting task at 45°.

Results: During the landing phase ACLr participants had increased hip flexion ($p < 0.003$) and transverse plane knee range of motion ($p = 0.027$). During the cutting phase, ACLr participant's previously injured limb had increased internal knee abduction moment compared to the control group ($p = 0.032$). No significant differences were reported between the previously injured and contralateral non-injured limb.

Conclusions: Previously injured participants demonstrated higher knee abduction moment and transverse plane ROM when compared to control participants during a game specific landing and cutting task.

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Dynamic Knee Joint Mechanics after Anterior Cruciate Ligament Reconstruction

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Running Title

Joint Mechanics ACL Reconstructed Athletes.

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Key Words: Osteoarthritis, Reconstruction, Knee, Joint Moments, Drop Land, Cut

INTRODUCTION

Paragraph Number 1 Anterior cruciate ligament (ACL) injuries are recognized as one of the most common and serious sports injuries with incidence rates of 61 ACL reconstructions per 100,000 person years in Australia (19). Reconstructive surgery is typically recommended after ACL injury, to restore the knee joint function and stability required for sports participation. Up to 80% of athletes who undergo surgery are unable to successfully return to their pre-injury-level of sport participation and therefore quit their sports (2). Athletes who are successful in rehabilitating from surgery and returning to their sport (ACLr participants) have been shown to be at an increased risk of repeated ACL injury to both the previously reconstructed knee and the contralateral knee (23, 25, 33). Additionally up to 50% of ACLr individuals will display signs of osteoarthritis (OA) 10 years post injury (32, 41, 28, 22, 24). Altered biomechanics and neuromuscular function as a result of the initial ACL injury, affecting both the injured and the contralateral limb, are likely to increase the risk of a repeated ACL injury (37) and degenerative joint disease (9).

Paragraph Number 2 ACLr participants have demonstrated altered lower limb kinematics and kinetics during everyday tasks such as walking (10, 4, 5, 34, 42), and moderately demanding tasks such as downhill running (38), stair ambulation and pivot combinations (21, 30, 40), single leg hopping (9, 26), drop vertical jumps (7, 12), and drop land and pivot combinations (31). These altered biomechanics were shown to occur in the sagittal plane at the hip (10, 7), knee (21, 9, 26) and ankle joint (21, 7), and in the frontal (38, 42) and transverse plane (30, 38, 31, 9, 34) at the knee joint. The altered frontal and transverse plane knee joint mechanics demonstrated by ACLr participants have been proposed as influential in the development of OA in an ACLr and ACL deficient population (36). Transverse plane hip kinetics, frontal plane knee kinematics, and sagittal plane knee kinetics have also been identified as risk factors potentially predictive of a second ACL injury from biomechanical measures during landing (27).

Paragraph Number 3 Few of these previous investigations have utilized tasks that closely replicate match situations. Ristanis and colleagues (31) have utilized the most match specific task which involved jumping from a 40 cm box, landing and pivoting at 90° to walk away. Bush-Joseph et al. (4) utilized a jog and diagonal cut task as one of their higher demand activities. These tasks are definitely advancements on the previous drop vertical jump and stair descent and pivot tasks, however they still lack the unanticipated and high intensity nature of match situations. Due to the fact that ACL injury rehabilitation aims to return individuals to full competitive participation in their sport, measurement of the performance of these ACLr participants during tasks that replicate match conditions is essential, in order to accurately identify altered joint mechanics that may predispose ACLr individuals to repeated ACL injury or the development of OA.

Paragraph Number 4 The assessment of lower limb mechanics during this novel drop-jump land and cut task will provide new information on any biomechanical adaptations present in ACLr participants during the performance of high risk movement tasks. This information may highlight risk factors for ACL re-injury and or the development of OA, as well as inform therapists regarding the design of rehabilitation protocols. 3D kinematics and kinetics of the hip and knee were measured for both legs during the land and for the push off leg during cutting in both directions. Athletes competing in field and court sports such as soccer and basketball regularly complete similar tasks, for example catching a rebound in basketball and following landing performing a side cut to evade an opponent. Both landing and cutting are reported to be high risk movements for the occurrence of ACL injury (16). A prospective study design to identify factors predicting repeat ACL Injury and or OA was not possible with this cohort, therefore the lower limb mechanics of ACLr participants was compared to a contralateral and non-injured control leg to identify any altered joint mechanics that may predispose ACLr individuals to repeated ACL injury or the development of OA. The purpose of this study was to evaluate and compare the lower limb kinetic and kinematic landing performances of ACLr individuals, against the contralateral non-injured limb and a healthy control, during the performance of a maximal drop-jump land and unanticipated cutting task.

METHODS

Paragraph Number 5 **Participants:** Eighteen participants who had previously undergone ACL reconstruction and rehabilitation (ACLr participants) (Males n=9, age 26 ± 4 years, height 1.78 ± 0.1 m, mass 81.74 ± 19.42 kg, time since injury 5 ± 3 years, Females n=9, age 22 ± 2 years, height 1.69 ± 0.06 m, mass 66.21 ± 7.51 kg, time since injury 4 ± 2 years) were recruited for the present investigation. All ACL reconstructions performed on the ACLr participants in this study utilized an autograft; the majority of participants received a hamstring tendon graft (n=17) and one of the male participants received a patellar tendon graft.

Paragraph Number 6. **ACLr Participant screening:** Only participants with a unilateral, non-contact or indirect-contact ACL injury, without additional lower limb injury 6 months prior to testing, were included in the study. ACLr participants were also required to be fully rehabilitated (cleared by their physiotherapist and surgeon) following ACL reconstructive surgery and back in full participation (training and competitive matches) in their chosen sport. All previously ACL injured participants were also required to pass two separate screening assessments, an IKDC, and a Functional Screening Protocol. The IKDC knee evaluation form (17) is a knee-specific measure of symptoms, function, and sports activity. It was utilized to ensure full rehabilitation of the ACLr participants. The Functional Screening Protocol consisted of a battery of four functional ability hopping tests (18) to assess adequate levels of symmetry and functional ability for the previously injured limb. Utilizing this screening protocol several potential ACLr participants were excluded from participation.

***Paragraph Number** 7* A further 18 gender, height, mass and sport matched participants who had no history of knee injury (control) were also recruited for the present study (Males n=9, age 22 ± 3 years, height 1.81 ± 0.09 m, mass 80.39 ± 5.36 kg, Females n=9, age 22 ± 2 years, height 1.67 ± 0.07 m, mass 63.81 ± 6.12 kg). Control participants had no history of serious lower limb injury and were injury free for a period of six months prior to testing. All participants competed in their sport at a high standard categorized by their sport team's division and years of playing experience (>8 years). Approval for the participation of human participants in this investigation was granted by the University of Limerick Research Ethics Committee.

Paragraph Number 8 **Experimental Protocol:** All participants completed an informed consent form. Participants wore athletic footwear of their own choosing, a tight fitting top and high-cut running shorts. Following measurement of height and mass participants completed a warm-up of a ten minute jog followed by light stretching. Limb dominance was assessed using three independent tests; the leg classed as dominant in the majority of tests was identified as the dominant leg. The tests were: the leg used to kick a ball as far as possible, the leg used to perform a single leg land and the leg used to regain balance when pushed from behind. Golden et al., (13) utilized three similar tests, the inclusion of three separate assessments allowing for a conclusive decision on the dominant limb. Maximum drop-jump height was assessed by a chalk mark imprinted on a wall from the participant's chalked palm during a maximum drop-jump from a 0.30 m bench.

Paragraph Number 9 A total of 45 reflective markers were placed on each participant. Rigid four marker clusters were placed on both thighs and shanks, and marker trios were placed on the pelvis (left PSIS, sacrum and right PSIS) to define segment rotations. The remaining markers defined hip and knee joint centers (greater trochanters and femoral epicondyles). Reflective markers were placed by the same individual on each participant. This marker set has been used previously in similar investigations (29) and has been reported as the most optimal non-invasive method of estimating segment rotations (1).

Paragraph Number 10 Kinetic and kinematic data were collected via Cortex software (Motion Analysis Corporation, v5.0, Santa Rosa, CA) during a maximal drop-jump land and unanticipated cutting task using two AMTI force platforms (1000 Hz) and six Eagle infrared Motion Analysis Corporation cameras (500 Hz).

Paragraph Number 11. A maximal drop-jump land and unanticipated cutting task assessment was designed to replicate demanding match situations within a laboratory environment. The task involved performing a drop-jump from a 0.30 m bench, to tap a target suspended at a previously recorded maximum drop-jump height. The suspended target acted as a trigger for a directional cueing system which indicated to the participant on landing the direction of the 45° run/cutting maneuver (See Figure 1).

Paragraph Number 12 Following a number of practice trials and a static trial, participants completed a minimum of 20 trials of the dynamic task; ten successful trials in each direction were required from each participant. Successful trials required the participant to run in the correct cutting direction as directed by the visual cue, through the mapped out pathway (See Figure 1). Both feet were required to land on their respective force plates during the jump land. Participants received 1 minute rest between trials (26) to prevent the potential effects of fatigue.

Paragraph Number 13 **Data Reduction:** Cortex (Motion Analysis Corporation, Santa Rosa, CA, USA) was used to track and export raw 3D coordinate data. The raw coordinate and ground reaction force data were low-pass filtered with a fourth-order Butterworth filter with a 12 Hz and 50 Hz cut off frequency respectively. The thigh, shank and foot segments were modeled as an assembly of cones, and the pelvis was modeled as a cylinder in Visual 3D^{TM} (C-Motion, Rockville, MD, USA). The local coordinate system and joint centers of these segments were defined from a static trial. Right-handed Cartesian local coordinate systems for the pelvis, thigh, shank and foot segments of the left leg were defined to describe position and orientation of each segment; this was mirrored in the frontal and transverse planes for the right leg to ensure consistent identification of anatomical movements for both legs. Three-dimensional knee and hip angles were calculated using a joint coordinate system approach. Joint centers were denoted by the midpoint between the medial and lateral calibration markers for the knee joint and one quarter the distance between the greater trochanter markers in the medial direction for the hip joint. Body segment parameters were estimated (8), and joint moments were represented in the joint coordinate system and resolved relative to the distal segment reference frame. The joint moments were defined as the internal resultant moments, similar to previous investigations (7, 29) and normalized to body mass and height (Nm/kg.m). The landcut task was separated into two distinctive regions for analysis; the initial landing and the final pushoff or cut. The start of landing and the end of cutting were identified as the instant when the vertical ground reaction force exceeded or fell below 10 N respectively. Participants utilised a variety of solutions to conduct the landcut task therefore only the initial high impact landing period and final push off or cut regions were identified for analysis. Any transition between these two regions was excluded from analysis. The initial landing period was characterized by a number of high impact peaks. Any transition period including any actions such as foot repositioning were excluded from analysis. The push off or final cut region was characterized by a smooth peak just prior to take off. Data were normalized to 1001 points for representation in ensemble curves.

Paragraph Number 14 Several discrete measures were calculated during the various phases of the task (i.e. the first 40 ms of the landing phase, the entire landing stance phase, and the entire cutting stance phase). See Supplemental Digital Content 1 (Illustration of discrete variables calculated during landing for a sample angle curve) for an illustration of these variables. Touchdown (TD), peak angles, peak angular excursion range of motion (ROMmax) and peak moments of the hip and knee were reported in all planes during the entire landing stance phase. Peak angles, angular range of motion (ROM), and peak moments of the hip and knee were reported in all planes during the first 40 ms of the land and the entire cutting stance phase. ACL injury is reported to occur during the first 40 ms of the landing phase (20) hence it was utilized for additional analysis.

Paragraph Number 15 **Statistical Analysis:** Mean differences between ACLr and control participants (ACLr previously injured limb versus dominance matched control limb), and within ACLr participants (ACL reconstructed limb versus contralateral injury free limb) for each of the above discrete measures for hip and knee joint angles and moments, were compared using a repeated measures ANOVA. Leg and trial were within-participant factors, and ACL injury status was the between-participant factor. Significance for all tests was set at $p < 0.05$. All statistical analyses were performed using SPSS (PASW v18.0, IBM Inc. Armonk, NY). Effect sizes are reported using partial eta^2 (ηp^2). It was calculated using the formula: $\eta p^2 = SS^{effect}/(SS^{effect} + SS^{error})$, where SS^{effect} = effect variance and SS^{error} = error variance. Interpretation of effect size was based on the scale for effect size classification of Hopkins (15). This scale is based on *f*-

values for effect size and these were converted to ηp^2 using the formula: $f = (\eta p^2/(1- \eta p^2))0.5$. Consequently, the scale for classification of ηp^2 was < 0.04 = trivial, 0.041 to 0.249 = small, 0.25 to 0.549 = **medium**, 0.55 to 0.799 = ***large***, and >0.8 = ***<u>very large</u>***.

RESULTS

Paragraph Number 16 **Landing Phase:** Table 1 presents a summary of the significant differences present at the hip and knee joint in the frontal and transverse plane joint angles during landing. No significant differences were found between ACL reconstructed limb and non-injured contralateral limb of ACLr participants. Differences between the ACL reconstructed limb of ACLr participants and the dominance matched leg on the control participants were found during the initial 40 ms during the entire stance phase of the land. Control participants landed with a more extended hip at touchdown (see Figure 2B) and throughout the landing phase, and also had more frontal plane ROM than ACLr participants when the control limb was compared to the ACL reconstructed limb. At the knee the ACL reconstructed limb had increased external-internal rotation ROM, during the first 40 ms and the entire landing phase when compared to the control limb. Table 2 presents a summary of the significant differences present at the hip and knee joint in the 3D joint moments during landing. No differences in 3D joint moments were shown between the ACL reconstructed limb and contralateral limb of the ACLr participants during landing. In the initial 40 ms of the land the ACL reconstructed limb had decreased extension moment when compared to the control limb, providing decreased resistance to flexion at the knee.

Paragraph Number 17 **Cutting Task:** Table 3 presents a summary of the significant differences present at the hip and knee joint in the 3D joint angles during cutting. At the knee the ACL reconstructed limb had more knee flexion than the control limb. At the hip the ACL reconstructed limb was more flexed than the control limb throughout the cutting component similar to the landing component of the task. The hip of the ACL reconstructed limb also had less transverse plane ROM compared to the control limb. Table 4 presents a summary of the significant differences present at the hip and knee joint in the 3D joint moments during cutting. No differences in 3D joint moments were shown between the ACL reconstructed limb and contralateral limb of the ACLr participants. At the hip the ACL reconstructed limb of the ACLr individuals had decreased extension moment when compared to the control limb. At the knee the ACL reconstructed limb of the ACLr individuals had increased abduction moment when compared to the control limb (see Figure 2A).

DISCUSSION

Paragraph Number 18 The purpose of this investigation was to determine whether athletes who have had ACL reconstruction exhibit altered lower limb biomechanics during a match specific task. We found increased hip flexion and transverse plane ROM in ACLr participants during landing, and increased internal knee abduction moment in ACLr participants during cutting when compared to the control limb. No differences were found between the ACL reconstructed limbs and contralateral limbs of the ACLr participants. These findings suggest long term adaptations occur during landing and cutting tasks after ACL reconstruction

Paragraph Number 19 ACLr participants in this investigation had a more flexed hip during landing which was in contrast to previous work (7). Poor neuromuscular control of the trunk has been linked with the increased risk of lower limb injuries. Zazulak et al., (43) have identified deficits in neuromuscular control of the trunk and core proprioception as predictors of knee and ACL injury in female athletes. Paterno et al., (27) also reported that decreased postural stability predicted repeated ACL injuries. Neuromuscular control of the trunk, measured by trunk displacement (43) has been shown to result in concurrent increases in hip and knee flexion (3) potentially resulting from a kinetic chain of summation of forces from an unstable trunk with excessive displacement to the increased flexion at the hip in the case of these ACLr participants. It may therefore be plausible that the increased flexion at the hips of the ACLr participants may originate from deficits in trunk control, which may increase risk of repeated ACL injury.

Paragraph Number 20 Frontal plane hip joint kinematics and kinetics have received limited if any research attention in an ACLr population. In the current investigation the ACL reconstructed limb had increased frontal plane ROMmax at the hip when compared to the control limb during landing. The average difference between groups was ~1° and with a small effect size, this difference was not considered large enough to merit discussion as a potential factor to increase either the risk of re-injury or the development of OA. The ACL reconstructed limb of the ACLr participants also showed altered transverse plane hip kinematics in comparison to control participants with less transverse plane ROM during the cutting movement. The difference in ROM between the groups was small at ~5° with a small effect size. Altered transverse plane hip kinematics have not been previously demonstrated in ACLr participants. Decreased transverse plane hip ROM has been linked with increased frontal plane motion at the knee (35). This compensation effect down the kinematic chain may explain the transverse plane ROM at the knee in the ACLr participants in this investigation.

Paragraph Number 21 ACLr participants had similar sagittal plane knee kinematics to *control* participants during landing. This was in agreement with previous investigations utilizing stair climbing and landing tasks (21, 7) but in contrast to a previous investigation utilizing landing from a horizontal hop (9). Both limbs of the ACLr participants and the control limb had average knee flexion angles greater than 20° at initial contact (ACL reconstructed limb = -24.4° ± 5.9°, NI= -23.1° ± 4.6°, Control= -22.1° ± 5.1°) and throughout the landing stance phase. Paterno et al., (27) did not find any link between decreased knee flexion and repeated ACL injury; therefore it is likely that any increased risk of repeated ACL injury in this population is not due to decreased knee flexion.

Paragraph Number 22 Previous investigations of walking, jogging and jog and cut tasks have reported reductions in external knee flexion moment in the ACL reconstructed limb when compared to a healthy control (39, 4). By contrast, the current investigation demonstrated less internal knee extension moment in the ACL reconstructed limb compared to the control limb during the initial 40 ms of the landing. As the external joint moment is balanced by the net internal joint moment produced by the ligaments and muscles, the external moment should be mathematically equal and opposite of the internal moment. It is likely that the demands of landing from a maximal drop jump may elicit different knee joint kinetics than reported by Bush-Joseph et al., (4) during a jog and cut task. This reduced internal knee extension moment would provide decreased resistance to knee flexion when compared to the control limb during the initial landing and is not likely to increase risk of repeated ACL injury as knee flexion moment is associated with decreased ACL strain (11).

Paragraph Number 23 In the frontal plane, increased knee abduction and adduction have been associated with the ACL reconstructed limb when compared to a control limb. There were no differences between the three-dimensional knee abduction ROM values reported in the ACL reconstructed limb or control limbs of the present investigation during the landing or cutting component of the task. The average of the abduction ROM values for each group during the landing component of the task (ACL reconstructed limb =7.23°, NI=7.47°, control=7.25°) were below what would increase risk of re-injury according to both Paterno et al., (27) and Hewett et al., (14) (~16.2° and 9° respectively). Tashman et al., (34) have reported increased knee adduction in the ACL reconstructed limb of ACLr individuals when compared to the contralateral limb. This was linked with the higher incidence and faster progression of knee OA (6). There were no such differences in knee adduction angles between the ACL reconstructed limb and contralateral limb in the present investigation. Tashman et al., (38) reported differences in knee adduction between ACL reconstructed limb and contralateral limbs via radiographic stereophotogammetric analysis. An investigation similar to this investigation utilizing skin based markers, comparing the ACL reconstructed limb to the NI during single leg hopping (9) also failed to show differences in knee adduction.

Paragraph Number 24 Increased internal abduction moment at the knee has been suggested as a predictor of OA at the knee, and has been demonstrated in ACLr participants during walking gait (5, 42) when compared to a matched control group. The present investigation reported similar findings with the ACL reconstructed limb of the ACLr participants demonstrating increased internal knee abduction moment during the cutting component of the task. The ACL reconstructed limb showed an 11% larger peak knee abduction moment than the control limb, with a small effect size. Increased knee abduction moments have been previously linked with the development of OA (5, 42), the proposed mechanism involves increased loading on the medial compartment of the knee. The results of the current study support these previous investigations (5, 42) by reporting larger internal knee abduction moments during match specific tasks, in ACLr individuals who have returned to sport. The internal knee abduction moments present in the ACL reconstructed limb of participants in the current study are larger than the control limb of the control participants but not the contralateral limb. It is especially interesting that this difference in knee abduction moment occurred during the unanticipated component of the task (the cut).

This may indicate that reaction to unanticipated tasks and decision making should be considered as a key component of ACL rehabilitation and OA prevention programs.

Paragraph Number 25 Increased transverse plane range of motion at the knee has been demonstrated at the knee in ACLr participants, during low impact stair descent and pivot (30) and high impact land and pivot tasks (31). The present investigation also reported increased transverse plane ROM and ROMmax on the ACL reconstructed limb when compared to the control limb during the initial 40 ms and the entire landing phase respectively. The values in the present investigation for transverse plane ROM are much smaller than that reported by Ristanis et al., (30, 31), (ACL reconstructed limb: 9.31° Control: 6.94° (Present Investigation) ACL reconstructed limb: 21.68° Control: 19.01° (Ristanis et al., (30)). This may be due to the pivot required by Ristanis et al., (30, 31) which was 90° as opposed the 45° cutting angle of the present investigation. The relative difference between the groups is similar in both investigations, but with a small effect size in the present investigation. Ristanis et al., (30, 31) concluded that the initial ACL injury caused the increased transverse plane ROM and that the surgical intervention and rehabilitation performed did not restore this to normal levels. A similar assumption cannot be drawn in the present investigation as both the ACL reconstructed limb and contralateral limb have similar levels of transverse plane knee ranges of motion. It is interesting that these differences in transverse plane ROM at the knee occur during the initial 40 ms of landing. Decreased control of knee rotation during this high risk component of the landing movement may increase the risk of repeat ACL injury and merits consideration in the future design of ACL rehabilitation programs.

Paragraph Number 26 It is clear from these results that the main differences were found between the control and ACLr populations rather than between the ACL reconstructed limb and contralateral limbs of the ACLr participants. Based on these data it appears that the surgical and rehabilitation interventions were successful in allowing the ACLr participants to regain similar lower limb biomechanics in both the ACL reconstructed limb and contralateral limb, but significant differences remain between the ACLr and control populations.

Paragraph Number 27 These altered lower-limb biomechanics are especially relevant to practitioners as they occurred during a match specific high intensity unanticipated task, which has not been utilized previously. These altered lower-limb biomechanics characterized by the ACLr group may therefore be risk factors the occurrence of repeated ACL injury or potentially for the development of OA in those who return to competitive action their sport.

Paragraph Number 28. Further investigations utilizing tasks that replicate competitive sporting demands with an ACLr population are required. No significant differences were reported between the ACL reconstructed limbs and contralateral limbs of the ACLr participants, which may have been due to the overall bi-lateral nature of the task. A similarly demanding and match specific task of a more single leg nature will further explore any compensation present within the ACLr participants ACL reconstructed limb and contralateral limbs. The differences present between the ACL reconstructed limb and control limbs in knee abduction moment and transverse plane knee range of motion support previous investigations identifying these variables as risk factors for the development of OA. The similarity of these variables in the ACL reconstructed limb and contralateral limbs of the ACLr participants may, in this population, indicate that the development of OA is not to be solely attributed to these factors. Therefore, the structure and degradation of the ACL reconstructed limb knee joint from the initial injury and surgical reconstruction (e.g. meniscal damage and bone bruising) in combination with these joint mechanics may lead to OA development. Prospective studies investigating the contribution of these knee joint mechanics in combination with varying levels of initial joint damage is merited.

Paragraph Number 29 There are some limitations to the current study. Although the risk of re-injury and development of OA is postulated no measurement of joint degeneration or incidence of repeated ACL injury took place. The adaptations present in the ACLr group during completion of a match specific task may highlight risk factors for the occurrence of these events and merit future investigation. Longitudinal Assessment of ACLr post-surgery patient's joint mechanics during demanding tasks or cross sectional research comparing ACLr patients who have returned to sport against those who have developed OA is also merited.

Paragraph Number 30 On the basis of the research outcomes obtained for the population tested, the following conclusions can be drawn:

- The ACL reconstructed limb of ACLr individuals performed a drop-jump land and cut task with similar hip and knee joint kinematics to that of the contralateral limb.
- ACLr participants performed a drop-jump land and cut task with increased hip flexion when compared to a control limb.
- The ACL reconstructed limb of ACLr participants performed the cutting component of the task with greater internal knee abduction moment than a control limb.
- The ACL reconstructed limb of ACLr participants performed the landing component of the task with greater transverse plane range of motion at the knee than a control limb.

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CONFLICT OF INTEREST: All authors declare no conflict of interest.

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Figure Captions

Figure 1: Illustration of the Drop-Jump-Land and Cut Task Set-Up

Figure 2: Ensemble curves for A) internal knee abduction adduction moment and B) hip flexion angle for ACLr and nACL groups. Shaded areas with asterisk highlight location of significant differences between groups.

Supplemental Digital Content (13-00430 SDC1-300dpi.tiff): Illustration of discrete variables calculated during landing for a sample angle curve.

Table 1. Significant differences in average 3D Joint Angles of hip, and knee during landing. Group differences (°), Partial eta^2 (ηp^2) and p-values are presented. Medium ηp^2 values are shown in **bold.**

1st 40 ms of Landing		**ACL Reconstructed**	**Control**	Diff	ηp^2	p-value
Hip	Max Flexion (°)	25.91	15.71	10.20	**0.25**	0.003
Knee	Ext-Internal Rotation ROM (°)	5.04	3.46	1.58	0.13	0.035
Entire Landing Stance Phase		**ACL Reconstructed**	**Control**	**Diff**	**ηp^2**	**p-value**
Hip	TD Flexion (°)	21.06	11.67	9.38	0.24	0.003
Hip	Max Flexion (°)	44.70	31.23	13.47	**0.27**	0.002
Hip	Abduction-Adduction ROMmax (°)	5.42	4.04	1.39	0.17	0.015
Knee	Ext-Internal Rotation ROMmax (°)	9.31	6.94	2.34	0.14	0.027

Table 2 Significant differences in average 3D Joint Moments of the knee during landing. Group differences (Nm/kg.m), Partial eta^2 (ηp^2) and p-values are presented.

1st 40 ms of Landing		**ACL Reconstructed**	**Control**	Diff	ηp^2	p-value
Knee	Max Extension (Nm/kg.m)	0.850	1.02	0.172	0.18	0.012

Table 3. Significant differences in average 3D Joint Angles of hip, and knee during cutting. Group differences (°), Partial eta^2 (ηp^2) and p-values are presented. Medium ηp^2 values are shown in **bold.**

Cutting		**ACL Reconstructed**	**Control**	Diff	ηp^2	p-value
Hip	Max Flexion (°)	55.23	36.77	18.47	**0.36**	<0.001
	Min Flexion (°)	22.03	4.23	17.80	**0.40**	<0.001
	Int-External Rotation ROM (°)	17.85	22.85	5.00	0.19	0.01
Knee	Max Flexion (°)	-37.09	-29.84	7.25	0.12	0.044

Table 4. Significant differences in average 3D Joint Moments of hip, and knee during cutting. Group differences (Nm/kg.m), Partial eta^2 (ηp^2) and p-values are presented.

Cutting		**ACL Reconstructed**	**Control**	Diff	ηp^2	p-value
Hip	Max Extension (Nm/kg.m)	0.591	0.762	0.172	0.16	0.02
Knee	Max Abduction (Nm/kg.m)	0.303	0.232	0.071	0.14	0.032

Figure 1
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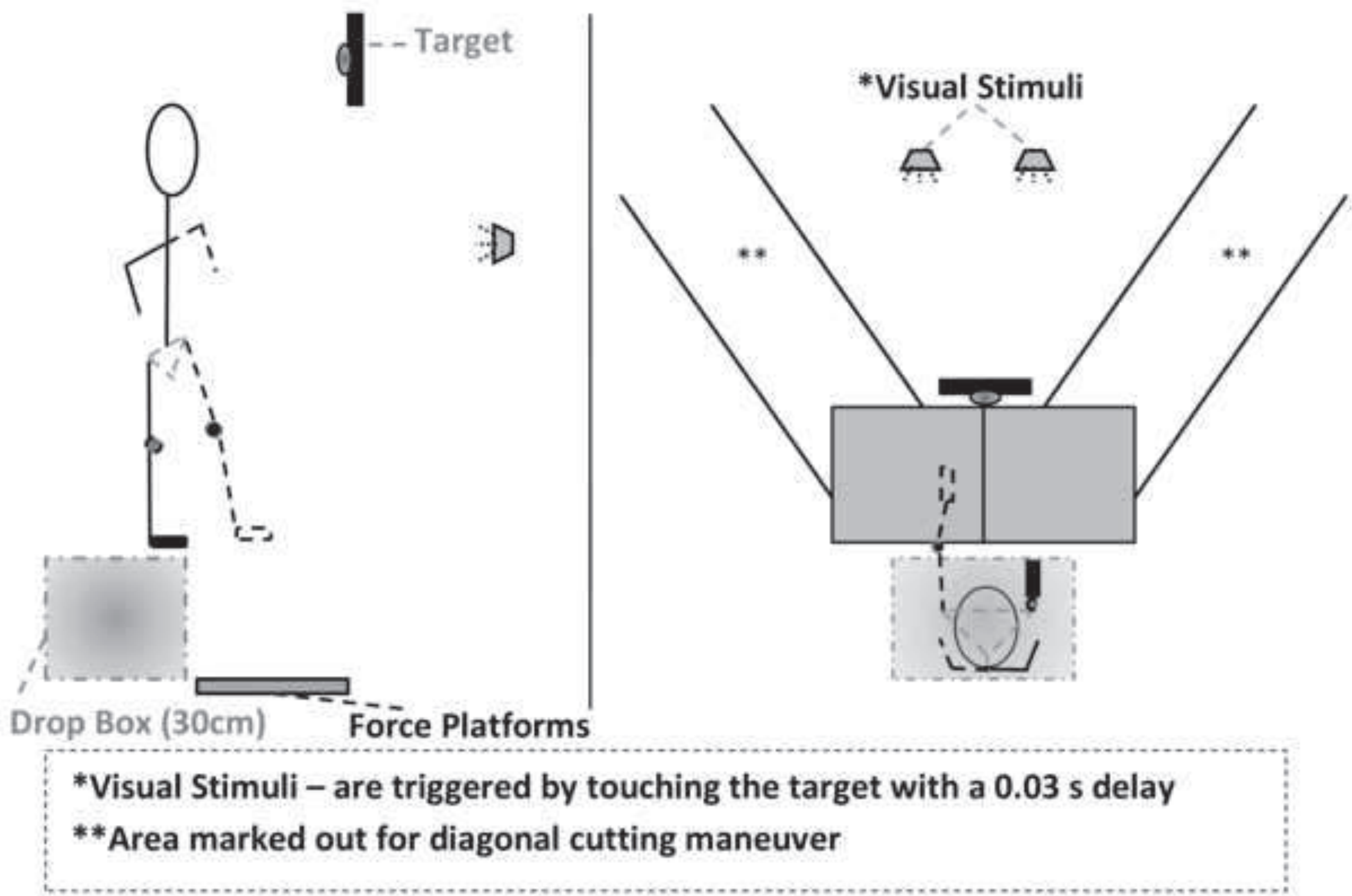

Figure 2
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